Surface Pion Condensation in Finite Nuclei

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We conjecture the occurrence of pion condensation in finite nuclei due to the recent experiments performed at RCNP [1, 2]. We start with the relativistic mean field (RMF) theory, which is quantitatively very successful. This theory does not include pions, which should be the most important ingredient in hadron physics. In fact, the Lagrangian of the relativistic mean field (RMF) theory is

$$\begin{aligned} \mathcal{L} &= \bar{\psi}[\imath\gamma^\mu\partial_\mu - M - g_\sigma\sigma - g_\omega\gamma^\mu\omega_\mu - g_\rho\gamma_\mu\tau^a\rho^{\mu a} - e\gamma_\mu\frac{(1-\tau_3)}{2}A^\mu]\psi \\ &+\frac{1}{2}\,\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2 - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 \\ &-\frac{1}{4}H_{\mu\nu}H^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{4}c_3(\omega_\mu\omega^\mu)^2 \\ &-\frac{1}{4}G_{\mu\nu}^aG^{a\mu\nu} + \frac{1}{2}m_\rho^2\rho_\mu^a\rho^{a\mu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\ , \end{aligned} \tag{1}$$

where the field tensors H, G and F for the vector fields are defined through

$$\begin{aligned} H_{\mu\nu} &= \partial_\mu\omega_\nu - \partial_\nu\omega_\mu \\ G_{\mu\nu}^a &= \partial_\mu\rho_\nu^a - \partial_\nu\rho_\mu^a - g_\rho\,\epsilon^{abc}\rho_\mu^b\rho_\nu^c \\ F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu\ , \end{aligned} \tag{2}$$

and other symbols have their usual meanings. Here, σ denotes the scalar meson, ω the vector meson and ρ the isovector-vector meson. A denotes the photon [3].

This Lagrangian apparently does not include the pion. The pion term should be there, but this term is neglected in the RMF approximation due to the conservation of parity and isospin until now. By adjusting the parameters in the RMF Lagrangian to the existing data on binding energies and radii of proton magic nuclei, these parameters are fixed by Sugahara and Toki [3]. We find good descriptions of binding energies and radii. The goodness of the parameter sets have been demonstrated by calculating all the even-even mass nuclei in the entire mass region [4].

If we look, however, the hadron physics, the chiral symmetry and its spontaneous breaking are the essential ingredients for the successful description of the experimental data. The pion exchange interaction is discussed in Nuclear Physics in terms of the tensor force. Let us see this connection first. The pion exchange force in the non-relativistic expression is written as $\vec{\sigma}_1\cdot\vec{q}\vec{\sigma}_2\cdot\vec{q} = \vec{\sigma}_1\cdot\vec{\sigma}_2q^2 + \frac{1}{3}S_{12}$, where S_{12} is called tensor force. We can then see by direct calculations that the tensor force is much bigger than the central spin-spin force. Therefore, we can say that the pion exchange interaction is approximately the tensor force. Knowing this, let us see what we know about the contribution of the tensor force in light nuclei.

There is a variational calculations on the α particle [5]. According to this calculation about a half of the potential energy is caused by the tensor force. This essential effect of pions has to be there in the heavy system. Why then the RMF theory without pion works so well. We can say that the use of parameters as g_σ and g_ω mocks up the pion attraction effect.

Is there any place for the necessity of pion? The interesting place to look for the answer to this question is the pionic excitation of nuclei. The recent (p,n) experiments performed at RCNP show very interesting results [1, 2]. The Gamow-Teller transition strengths are carried largely by 2p-2h states. The pion response is found very small as compared with the theory predictions.

We propose to take the pion terms seriously now, which should be present in the lagrangian. For simplicity of writing, we write explicitly only the sigma and pion terms in the lagrangian density as,

$$\mathcal{L} = \bar{\psi}[i\gamma^\mu\partial_\mu - M - g_\sigma\sigma - g_\pi\gamma_5\gamma^\mu\partial_\mu\tau_a\pi^a]\psi + \mathcal{L}_{meson}. \tag{3}$$

We then assume that the expectation value of the pion field is finite. We write the equation of motion for nucleons and pions as,

$$[i\gamma^\mu\partial_\mu - M - g_\sigma\sigma - g_\pi\vec{\nabla}\pi^a\gamma_5\vec{\gamma}\tau_a]\psi = 0 \tag{4}$$

and

$$[\vec{\nabla}^2 - m_\pi^2]\pi^a = -g_\pi\vec{\nabla}\langle\bar{\psi}\gamma_5\vec{\gamma}\tau_a\psi\rangle. \tag{5}$$

The sigma meson and others follow the same equations of motion as the standard case. These equations tell the reason why we have not included the pion mean field until now. The source term of the pion Klein-Gordon equation is non-vanishing only when the parity and the isospin are mixed in the single particle state. This violation of the parity and isospin is caused by the pion term in the above Dirac equation for nucleons. Hence, the single particle state can be expressed as

$$\psi_{n,jm}(x) = \sum_{\kappa,t} W^n_{\kappa,t}\phi_{\kappa jm,t} \tag{6}$$

Here, $\phi_{\kappa jm,t}$ denote the eigen functions of nucleons without the pion mean field term. The summation over κ means the parity mixing and the summation over t the isospin mixing. We would call the case of non-vanishing pion mean field as surface pion condensation, since the pion source term involves derivative of the mean field. The source term is finite only around the nuclear surface.

We have discussed the possible occurrence of surface pion condensation in order to understand the recent (p,n) experimental data taken at RCNP. This suggestion is motivated by the missing pion contribution in the discussion of ground states of finite nuclei, while pions are essential for hadron physics. We expect a large modification to our understanding of nuclei. We are in the position to predict many observables, which are to be checked by experiments at RCNP.

References

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